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THE SOLAR CYCLE VARIATION OF CORONAL TEMPERATURE DURING CYCLE 22

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ABSTRACT In this paper we describe preliminary results of a collaborative effort to characterize the temperature structure of the corona utilizing co-spatial spectrophotometric observations during ascending phase of solar cycle 22. The data include ground-based intensity observations of the green (5303Å Fe XIV) and red (6374Å Fe X) coronal lines from Sacramento Peak. A difficulty in attempting to characterize the state of the coronal plasma is that the temperature, the absolute chemical abundances, and the coronal density irregularities all affect the observed emission. However, in this analysis a determination of plasma temperature *T* can be derived unambiguously from the intensity ratio Fe XIV/Fe X, since both the emission lines come from ionized states of Fe, and the ratios are only weakly dependent on density. The variation of the temperature within the ascending phase of solar cycle 22 will be discussed.

INTRODUCTION

Knowledge of basic physical conditions like temperature in the corona is fundamental to our understanding of the dominant physical processes that drive the corona and the terrestrial system via the interplanetary medium. There is currently a great deal of interest in interpreting various ground-based observations of the sun that are inputs to models of the earth's atmosphere. These topics constitute a strong motivation for examining the solar cycle related properties of the corona.

Very few accurate measurements have been made of the temperature of the inner corona. The EUV and XUV observations of the OSO and Skylab eras established the differential emission measures of the upper transition region and low corona (e.g. Withbroe 1977). In addition, spectral imaging characterized the temperature of structures that extend to greater heights and also the quiet low corona outside of active region loops (e.g. Feldman, Purcell and Dohne 1987). Recently, Guhathakurta *et al.* (1991, 1992) and Orrall *et al.*

(1990) determined the temperature structure of the inner corona utilizing co-temporal observations of the intensities of XUV, the coronal green line Fe 5303Å and the coronal red line Fe X 6374Å during the total solar eclipse of March 1988. These studies provide great promise for a systematic study of the variation of the average global temperature of the corona and the latitudinal variation of the temperature as a function of the phase of the solar cycle.

The most direct ground-based proxy of the coronal component of the solar EUV and UV emission is provided by the coronal forbidden lines such as the green line of Fe XIV at 5303 Å, the red line of Fe X at 6374 Å and the yellow line of Ca XV at 5694 Å. A surprisingly good correlation has been found between the variation of Lyman α and the intensity of the Fe XIV coronal green line (Pap *et al.* 1990). The green line coronal index shows a variation over the solar cycle similar to the UV irradiance (Donnelly 1989). For Cycle 21, it generally decreases until mid-1986, similar to Lyman α (Pap *et al.* 1990), and its maximum shows up two years later than the the sunspot maximum (Rybansky *et al.* 1987, Altrock 1988, 1990). These results indicate a strong physical relationship between the variation of UV irradiance and coronal indices (see also Barth *et al.* 1990).

OBSERVATIONS

Daily observations of the solar corona are made at the National Solar Observatory at Sacramento Peak with the Photoelectric Coronal Photometer (Smartt 1982). These observations have been made in the lines at 5303 Å and 6374 Å which are formed at approximate temperatures of 1 and 2 MK respectively in units of $10^{-6}B_\odot$, the brightness of the solar disk at the given wavelengths (Altrock 1990). The 1.1′ entrance aperture is scanned daily around the limb at 1.15 $R_\odot$. These data provide an extended, almost daily, uniform set of photoelectric observations of the corona that can be used to derive a long-term description of the morphology, evolution and temperature of the solar emission corona. The utility of the data set in the above context has been demonstrated by their use in several earlier papers on coronal structure and evolution (Fisher and Musman 1975, Fisher 1978, Sime *et al.* 1985, Altrock *et al.* 1987, Altrock 1988, and Sime *et al.* 1989). In Figure 1a, we have presented the daily average (here daily data are averaged over east and west limb) values of the observed intensities of the green and the red lines as a function of time at height $1.15R_\odot$ for the period 1984 through September 1991. In Figure 1b, we have presented the 27 day average of the above data set.

INTERPRETATION OF LIMB PROFILES

In order to interpret the observed intensities, we derive theoretical intensity profiles to be compared with the observations using the same general approach described in (Guhathakurta *et al.* 1992), where we assume the following model corona: (1) spherical symmetry along the line of sight, (2) collisional excitation processes, (3) ionization equilibrium distribution of ionic species, and (4) that the helium abundance $A_{He} = 0.0851$ (Allen 1973).

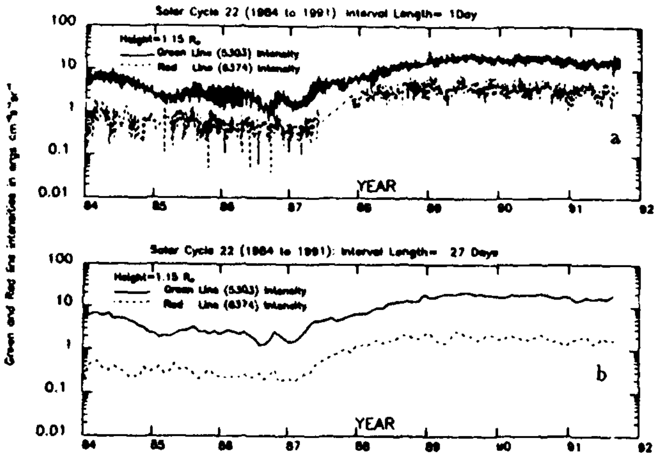

Fig. 1. a) The observed intensities (erg $cm^{-2}\ s^{-1}\ sr^{-1}$) of the red line I_r, and the green line I_g from Sacramento Peak, plotted as a time series from years 1984-1991. b) The observed intensities from Figure 1a has been averaged over 27 days.

The Intensity of the Forbidden Lines of Fe XIV and Fe X

The emissivity of these radiations can be written to appropriate accuracy in the general form

$$E_i = D_i(T)n^{\gamma_i}(\mathrm{erg\ cm^{-3}\ s^{-1} sr^{-1}}); \qquad (1)$$

where i=g for I_g and i=r for I_r. Here D(T) depends on the chemical abundances and the specific transitions as well as on the electron temperature T and to some extent on the radiation field. For forbidden coronal lines primarily excited by collisions but for which the radiation field is also important, γ has a value between 1 and 2.

Let the y-axis lie in the direction of the line-of-sight with its origin at the point where this axis intercepts the plane of the sky, and let y be expressed in units of the solar radius so that $r^2 = x^2 + y^2$. The intensity observed at a height x above the limb is as described below

$$I_i(x) = R_\odot \int_{-\infty}^{\infty} E_i(y)dy = 2R_\odot \int_x^{\infty} E_i(r)\frac{rdr}{(r^2 - x^2)^{\frac{1}{2}}} \qquad (2)$$

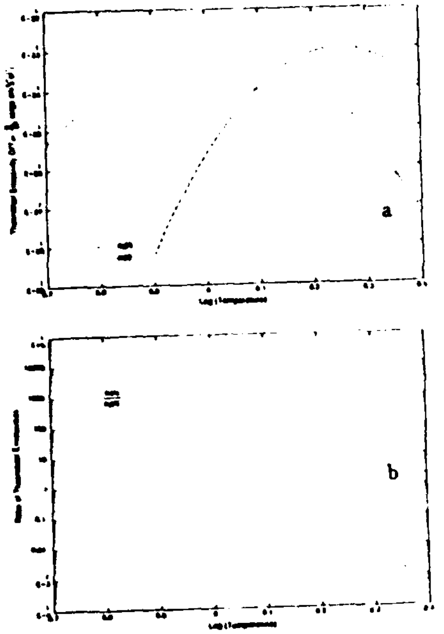

Fig. 2. a) The temperature dependence of the theoretical emissivity $D_g(T)$ for the coronal green forbidden line 5303 Fe XIV and $D_r(T)$ the red line 6374 Fe X. b) The predicted temperature dependence of the ratio $\frac{D_r(T)}{D_g(T)}$.

Using the same approach as in Guhathakurta *et al.* (1992), we can simplify the above equation and rewrite it as

$$I_i(x) = R_\odot\left(\frac{2\pi h_o}{\gamma_i}\right)^{\frac{1}{2}} x^{\frac{3}{2}} E_i(x_o)\exp\left[\frac{-\gamma_i(x-x_o)}{h_o x x_o}\right] \tag{3}$$

where h_o is a scale-height parameter, n_o is base density and x_o, is some reference height.

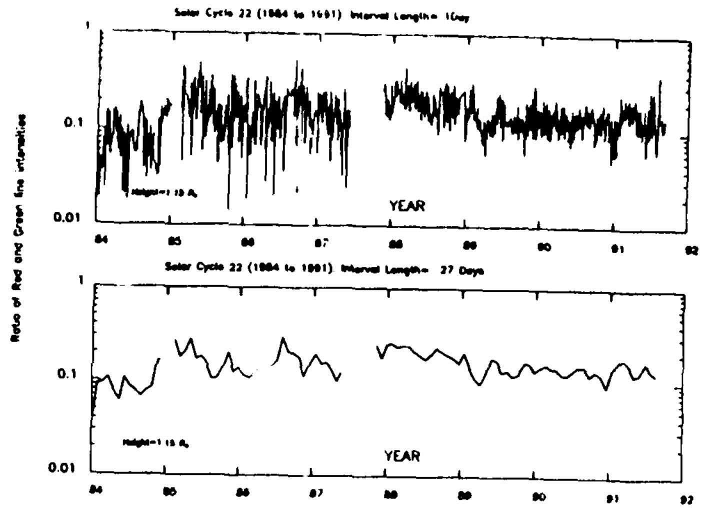

Fig. 3. a) Daily line ratio obtained from intensities Ir and Ig is plotted for years 1984-1991. b) 27 day average of the line ratio I_r/I_g is plotted for years 1984-1991.

THEORETICAL EMISSIVITY OF FE XIV, FE X

Mason (1975) has carried out a study of the excitation of the forbidden coronal lines 5303Å Fe XIV and 6374Å Fe X that takes account of both radiative and collisional processes. We have used Mason's excitation calculations for a dilution factor of 0.3, together with the ionization equilibrium calculations of Arnaud and Rothenflug (1985), and the abundances of Allen (1973) to calculate the emissivity of the green and red coronal lines, E_g and E_r, respectively. Because of the contribution of radiation to the excitation of these lines the density dependence of the emissivity in the region of interest is $n^{1.68}$ for 5303Å, and $n^{1.66}$ for 6374Å that is, the quantity γ_i of is 1.68 and 1.66 respectively. The quantities

$$D_g(T) = \frac{E_g}{n^{1.68}}, \quad D_r(T) = \frac{E_r}{n^{1.66}} \tag{4}$$

and their ratio are presented in Figures 2a and 2b, respectively.

TEMPERATURE DETERMINATION FROM EMISSION LINES

We determine the temperature of the inner corona (outside of active regions) in a manner similar to that outlined in Guhathakurta, *et al.* (1992). In this particular study, we have intensity measurements from two different states of ionization of the element Fe (Fe X, XIV). The intensity ratios $\frac{I_r}{I_g}$ and $\frac{I_r}{I_g}$ are very sensitive to temperature in the range between $10^{6.0}$ to $10^{6.3}$. From the previous analysis we have following equation for the intensity ratio:

$$\frac{I_r(x)}{I_g(x)} = .99 \left[\frac{D_r(T)}{D_g(T)}\right] n(x)^{-.02} \approx \left[\frac{D_r(T)}{D_g(T)}\right] \tag{5}$$

Theoretical values for the ratio $\frac{D_r}{D_g}$ is plotted in Figure 4. We notice that a dramatic change in the intensity ratio implies a small change in temperature and therefore the precise calibration of each individual observation has minor influence on the temperature determination. An uncertainty of one order of magnitude in the ratio of $\frac{I_r}{I_g}$ leads to an error of only ±12% in estimating temperature. Thus this method is a sensitive way of establishing coronal temperature for the inner corona. Inspection of the above equation shows that the intensity ratio is strongly varying function of temperature, T, but only weakly varying function of density, n.

In Figure 3, we present the intensity ratio I_r/I_g for the period 1984-1991, and in Figure 4, we present the average temperature variation of the inner corona during this period.

DISCUSSION

If a temperature variation existed in the corona, the red line should be emitted more strongly in the cooler regions and the green line from hotter regions. This was observed in the earlier work of Guhathakurta *et al.* (1992) where they analyzed XUV, red and green line data for a single day as a function of position angle. In this preliminary analyses where we have averaged the daily data over latitude we still observe a variation in coronal temperature depending on the phase of the solar cycle. In Figure 5, we have presented the temperature as a function of each year from 1984 through 1991 for clarity. We find that quite often the peaks in red line are associated with dips in green line intensity and vice versa. The average temperature during the years of maximum activity (1989 - Sept 1991) was 1.57±.03. During the rising phase of the cycle (1988) the average temperature was 1.52±.03 while during the declining phase (1984) of the cycle the temperature was 1.64/ + −.06. Two temperature minimum (1.52±.06) were observed that preceded and followed the temperature peak of 1.6MK around solar minimum (1986). Variation of temperature over latitude is much greater than the variation obtained from daily averages.

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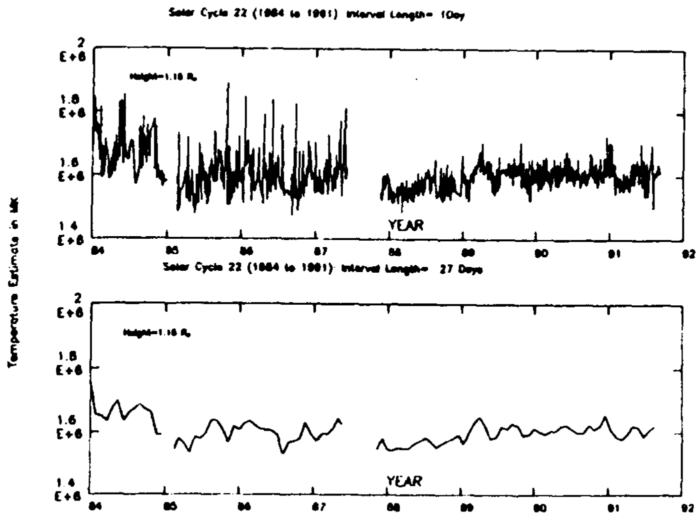

Fig. 4. a) Daily temperature derived from Ir and Ig line ratio at height 1.15 $R_\odot$ is plotted as function of time. b) 27 day average of the temperature is plotted for years 1984-1991.

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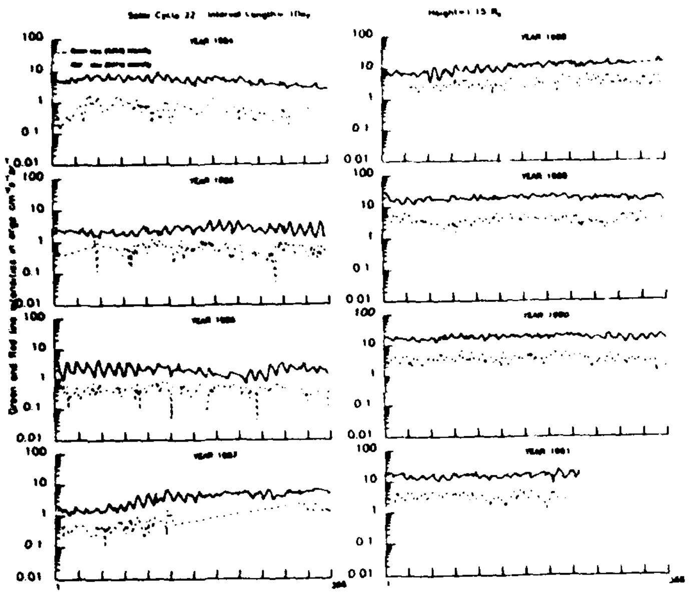

Fig. 5. Temperature as a function of years from 1984-1991

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